What does tomography have to say about mantle geochemistry?

Guy Masters

Summary by: Christine Reif

Introduction

This talk is divided into several sections. We first describe the data sets that go into 1D and 3D inversions for earth structure to allow you to evaluate what aspects of the models are robust. We follow this with a discussion of 1D models with particular emphasis on the possibility of a dense layer in the lower mantle and on the current status of possible compositional jumps in the upper mantle and transition zone. We then discuss the general nature of global 3D models of the mantle emphasizing the strong evidence for slab penetration into the lower mantle and the lack of evidence for a "stealth" layer. We close with a discussion of the possible physical causes of seismic anomalies in the mantle.

Data Overview

To understand what information we can gleam from tomography, we must first understand what data are fed into the inversions. Different seismic waves are sensitive to properties at different depths within the earth. The attenuation and dispersion of surface wave packets (Rayleigh and Love waves that circle the earth after an earthquake) provide constraints on upper mantle structure. The lower mantle is sampled by compressional, P, and shear, S, body waves. Lower mantle structure can be revealed by comparing the differential arrival time of two raypaths with the same source and receiver so the surface effects can be removed, for example ScS-S. Mode data are obtained by taking the spectrum of a seismogram. The peaks in the spectrum are the frequencies of the earth's modes of oscillations, the earth rings like bell after an earthquake. These single frequency peaks can be split into a several peaks by such things as anisotropy in the inner core. Mode data provide constraints on the earth's density distribution, as well as on the long-wavelength velocity distribution. From the global seismic network map it is easy to see that seismology suffers from a lack of data in the southern hemisphere. However, over the last 20 years we have accumulated over a million seismograms for analysis.

One-dimensionnal (1-D) models

The surface wave, body wave, and mode data are used in inversions to try to find a model that fits all the types of data. Using resolution analysis, it is possible to chose a combination of data that is sensitive to one parameter at one depth. The resulting density models are well constrained, and raising the density by 1% in a few hundred kilometer thick layer near the base of the mantle would wreak havoc on the mode data. Thus it is unlikely that a "stealth" layer exists though the complicated tradeoffs involved in modelling free oscillation frequencies means that we cannot rigorously preclude the existence of such a model.

Mineral physics has now provided reliable equations of state for most of the possible constituents of the mantle (though data for shear modulus are still lacking). Recent work indicates that a pyrolitic composition can fit the seismic data without any change in composition at the 660km or 410km discontinuity though, again, tradeoffs with temperature preclude us from saying the mantle is isochemical with absolute certainty.

Three-dimensional (3-D) models

Surface waves constrain the near-surface structure and body wave travel times. Particularly the times of direct S and P at distances from 25 to 100 degrees, constrain lower mantle structure. By plotting histograms of the travel time residuals for rays that turn at different depths in the mantle, we can observe negative (fast velocities) or positive (slow velocities) patterns (residuals are the difference between the observed differential travel time and that calculated using PREM). The most noticeable pattern is the difference in the histogram width of P and S with depth. The width of the histogram does not change for P with increasing depth in the mantle. However, the S histogram widens with depth and develops a bump corresponding to positive residuals (slower S travel times). These residuals are dominantly for rays which bottom in the central Pacific and under Africa in the bottom about 500km of the mantle.

The general trend observed in most of the tomography models is the large amplitude, long wavelength structure in the upper and lower-most mantle because they are thermal boundary layers while the mid-mantle contains low-amplitude slab-like fast features which surround broad regions of slow velocities. Radial correlation functions show the correlation of structure at different depths among the models. Some models show striking structure difference across the 660 mantle discontinuity, while others have only slight differences across the phase change.

Making models is a fine thing to do, but what can we learn about the properties of the inner earth? From the travel times we are able to calculate Vp (compressional, P, wave velocity), Vs (shear, S, wave velocity), Vc (bulk sound speed), and ρ (density). $\mu=\rho V_s^2$, $K_s = \rho (v_p^2-4/3*v_s^2) = \rho V_c^2$ where μ is the shear modulus and K_s is bulk modulus. Bulk sound speed relates to bulk modulus as the shear wave speed relates to the shear modulus. Vp is sensitive to mu so it is better to use Vc and Vs to separate out compressional and shear effects. The tomography models show the unintuitive result that Vc and Vs are anti-correlated in the lower mantle. Most mantle anomalies can be explained thermally, but this anti-correlation cannot be explained by thermal effects alone. Therefore, we are searching for combination of partial melt and chemistry changes in parts of the lower mantle to explain the anti-correlation. A new high pressure polymorph of perovskite which might appear in regions of elevated temperature in the lower mantle could be an explanation.

Discussion

Q. What is effect of topography on boundaries.

A. CMB has weak effect on data. There is a tradeoff with structure on either side of 410 and 660. Will include SS-S precursor data in next round of inversions and explitly include models of topography on the 410 and 660 (moho is already included).

Q. Harvard has a sharp change in structure at certain places at the 660km. Why?

A. That model has a break in the parameterization at that depth -- it should be noted that the data constraints on structure are changing at about this depth -- surface waves are dominantly constraining structure above this depth and body waves are dominantly constraining structure below. The tomographic models of different groups are least similar in the transition zone which also indicates that control of structure here is not as good as we would like.

Q. Have seismologists (re)looked at the correlation of seismic velocities with trace elements and heat producing elements?
A. This hasn't been done for several years and would be interesting to do again since the seismic models and the geochemical data sets have both improved.